[PS]Pre- and Post-Injection Vertical Seismic Profiling over the Southwest Regional Partnership's Phase II Fruitland Coal CO_2 Pilot*

Tom Wilson[1,2], Les Nutt[3], Ric Smith[3], Jitendra Gulati[3], Marcia Coueslan[3], Dwight Peters[3], Art Wells[2], Craig Hartline[4], George Koperna[5], and Bill Akwari[4]

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Abstract

In this study we report on the results of pre- and post-injection vertical seismic profiles acquired for the Southwest Regional Partnership (SWP) on Carbon Sequestration's San Juan Basin Fruitland Coal pilot test. The project is funded by the U.S. Department of Energy and is managed by the National Energy Technology Laboratory. The pilot test was undertaken in collaboration with ConocoPhillips as a joint enhanced coalbed methane recovery test and demonstration of CO_2 sequestration in deep, unmineable coal seams. The SWP conducted the pilot in the Upper Cretaceous high- rate, Fruitland-production fairway southwest of the northwest-trending basin hinge. CO_2 injection began July 30, 2008 and continued through August 14. 2009. During the 12-month injection period, approximately 319 MMCF, equivalent to nearly 18,407 short tons of CO_2, were injected into the Fruitland coals.

The pre-injection, vertical seismic profiles were completed on June 3-4, 2008. The post-injection surveys were acquired on September 17, 2009: a month after CO_2 injection was completed. The monitor VSPs were not surveyed until the reservoir was pressured down. Both pre- and post-injection surveys included a zero offset VSP and three offset VSPs. The zero-offset source was located 114 ft from the injection well along a 245 degree azimuth. Long offset sources were located 1498 ft from the injection well along a 216 degree azimuth, 1693 ft along a 34 degree azimuth, and 1942 ft along an azimuth of 349 degrees.

Elemental analysis through the lower Fruitland reveals thick coal seams in the intervals 2950-2970 ft, 2975- 2986 ft, 3048-3060 ft, and 3111-3136 ft. Compression- and shear-wave velocities were measured using Sonic Scanner from 285 ft to 3132 ft subsurface. Density was also measured as part of the Platform Express run. Synthetic seismograms are used to tie subsurface geology to surface 3D seismic in the area and

also to the VSP responses. Results from time lapse processing are preliminary. The WVU funded processing effort through Schlumberger continues.

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Panel 1

Pre- and Post-injection Vertical Seismic Profiling over the Southwest Regional Partnership's Phase II Fruitland Coal CO_2 Pilot

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Abstract

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The pre-injection vertical seismic profiles were completed on June 2nd and 3rd of 2008. The post-injection surveys were acquired on September 17th, 2009: a month after CO_2 injection was completed. The monitor VSPs were not run until the reservoir was pressured down. Both pre- and post-injection surveys included a zero offset VSP and three offset VSPs. The zero offset source was located 114 feet from the injection well. Long offset sources were located 1498 feet from the injection well along a 216° azimuth, 1693 feet along a 34° azimuth, and 1942 feet along an azimuth of 349°.

Elemental analysis through the lower Fruitland reveals thick coal seams in the intervals 2950' to 2970' subsurface, 2975' to 2986', 3048' to 3060' and 3111' to 3136 '.Compression and shear wave velocities were measured using the Sonic Scanner from 285 feet to 3132 feet subsurface. Density is also available from the Platform Express log suite. Synthetic seismograms are used to tie subsurface geology to surface 3D seismic in the area and the VSP responses. Results from time lapse processing are preliminary.

Primary Objective
Evaluate the potential for time-lapse offset VSP to identify the CO_2 flood front.

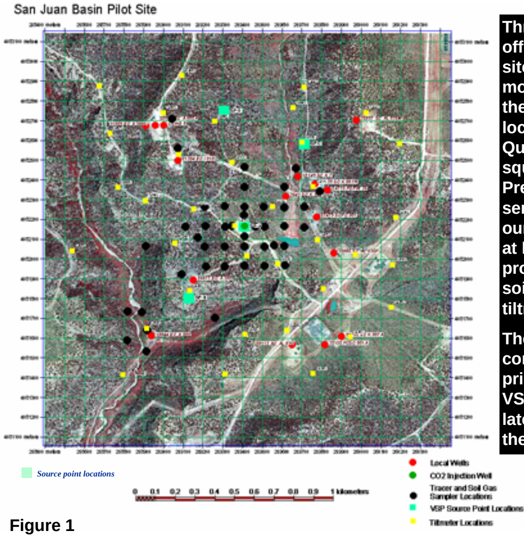
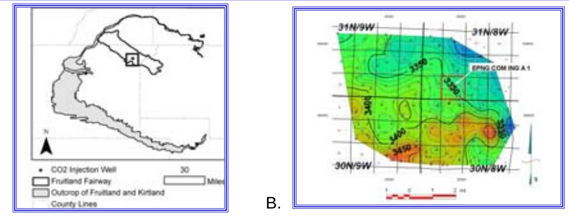


Figure 1

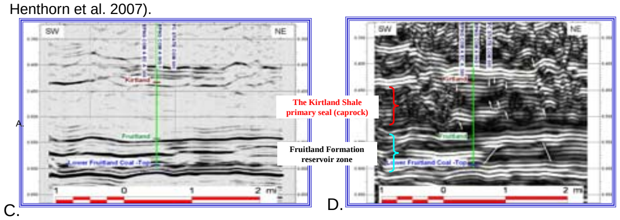
Three offset VSPs and one zero offset VSP were collected at the site providing baseline and monitor (post-injection views of the site). The source point locations are shown on the QuickBird image at left (green squares) (also see Figure 3B). Presence of archaeologically sensitive areas at the site limited our choice of offsets. The image at left also shows locations of producing wells, NETL tracer and soil gas sample points and tiltmeters.

The baseline VSP surveys were completed about two months prior to CO_2 injection. The monitor VSPs were surveyed 1.3 years later, just over a month following the completion of CO_2 injection.



A. B.

A) Regional location map and B) structure on the base of the Fruitland Formation (after Henthorn et al. 2007).



C. D.

C) Migrated stack line passing through the injection well (COM A ING 1) and two production wells (COM A 300 and FC STATE COM). D) Enhanced view reveals potential faults and fracture zones within the Fruitland Formation and Kirtland Shale. The VSP was run in the center COM A ING 1 well.

Figure 2

Background on the study

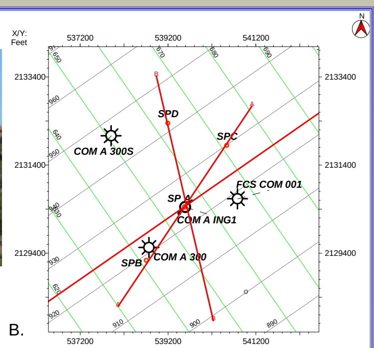
The study discussed in this poster was funded through a West Virginia University/ National Energy Technology Laboratory (NETL) contract. During the SWP's Phase II effort at the site, West Virginia University undertook several site characterization activities over the San Juan Basin pilot in support of NETL Monitoring, Verification and Accounting (MVA) team efforts. These activities were primarily intended to help locate possible CO_2 leakage pathways and identify additional locations of additional PFC tracer and soil gas observation points. The integrated studies were designed to help optimize estimation of the CO_2 escape volume if leakage were to occur. Collaborative efforts were also designed to complement and enhance the ongoing efforts of the Southwest Regional Partnership (SWP).

Site characterization activities included field and satellite based fracture mapping, subsurface mapping of the region using geophysical logs, evaluation of interferrometric synthetic aperture radar (InSAR) observations to accurately measure ground movements at the site, detailed electromagnetic surveys, lineament analysis of radar and Landsat imagery and 3D seismic interpretation (see locations in Figures 1 and 2). Additional discussion of these efforts are in Wilson et al. (2008 and 2009).

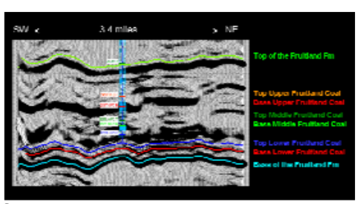
In support of the present study WVU and NETL initiated and funded logging operations of the ConocoPhillips EPNG COM A ING 1 injection well, helped plan and design the VSP time-lapse surveys and set up a separate contract with Schlumberger to fund additional time-lapse processing of the VSP data. Initial time lapse processing was completed in November of 2009. Significant differences in the acoustic properties of the Fruitland sequence attributable to CO_2 injection have not been detected. Additional time-lapse processing is still underway.

ConocoPhillips EPNG COM A ING 1 CO2 Injection Well

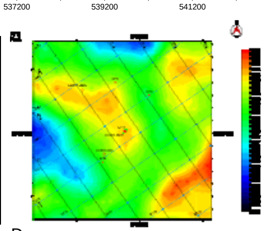
A.



B.



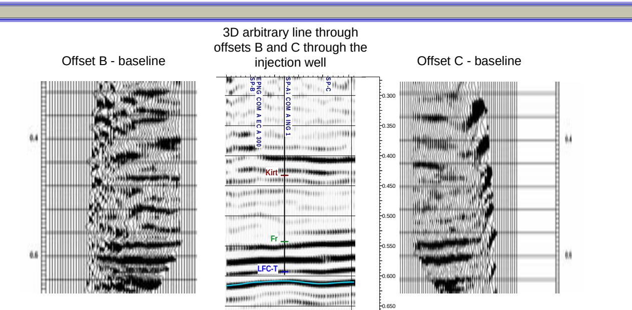
C.



D.

Figure 3

Sensors for the VSP survey were placed in the ConocoPhillips EPNG COM A ING1 CO2 injection well (Figure 3A). The locations of the source points A-D are shown along with surrounding production wells in B. The Fruitland sequence is highlighted in a seismic line from the 3D survey (C). The internal reflection response is complex and reflection discontinuity common. An isopach of the Fruitland sequence (D) reveals considerable variation in traveltime through the Fruitland reservoir interval.



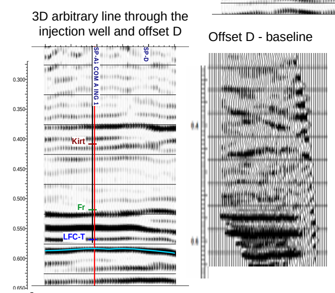


Figure 4

SWP Pre-Injection Vertical Seismic Profiles

Comparisons of the baseline (pre-injection) VSPs to bandpass filtered arbitrary lines extracted from 3D seismic that extend through the injection well and VSP source points (B, C and D) (see line location map Figure 3). The VSP data were collected for the Southwest Regional Partnership and processed by Schlumberger. (VSP displays, courtesy of Schlumberger, 2008).

Source offsets B and C lie along a northeast-southwest line (~N30E). Some relative time-shift between the 3D seismic and offset VSP event times was introduced to align interpreted event correlations and arrival times. Common midpoint locations in the VSP display increase in offset from right to left for Offset B and from left to right for offsets C and D. Midpoints extend at most to approximately half the distance between the injection well in which the geophones were placed and individual source point locations.

Acquisition and Processing Comments

The baseline and monitor VSP surveys (Figure 4, right) were collected using a 12 second duration Vibroseis upsweep from 8-120 Hz. Differences between baseline and monitor surveys often arise for a variety of reasons. In the present case, for example, heavy rains preceded the monitor survey while the initial baseline survey was conducted under dry conditions. Other differences between the baseline and monitor surveys unrelated to CO_2 injection include repositioning of the source at offset B (see Figure 3) to reduce distortion levels during the monitor survey, skipped shots during the baseline survey and differences in receiver depths in the recording well noted in the monitor survey. Offset VSP processing steps included true amplitude recovery, bandpass filtering (3 – 120 Hz.), amplitude normalization, median velocity filtering to separate downgoing and upgoing wavefields and waveshape deconvolution. Processing of the baseline and monitor data sets were identical. The differenced data sets (monitor – baseline) retain considerable amplitude at all recording times but the differences are especially noticeable for Offset D (Figure 5, see panel 2). Additional processing included crossequalization (e.g., Ross et al., 1996) and non-rigid matching (Nickel and Sonneland, 1999). Refinements to the VSP processing workflow continue to be tested.

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Panel 2

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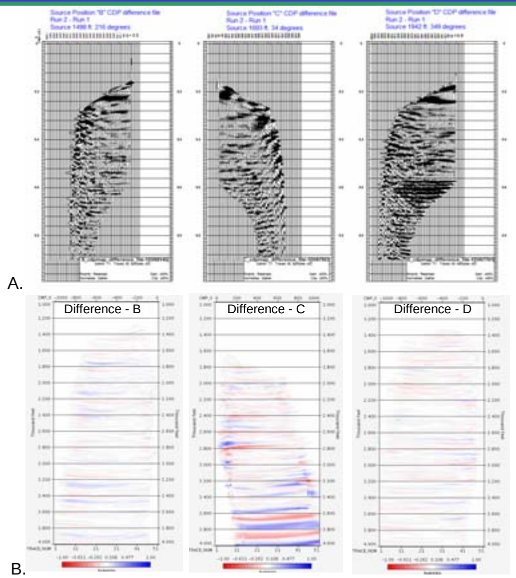


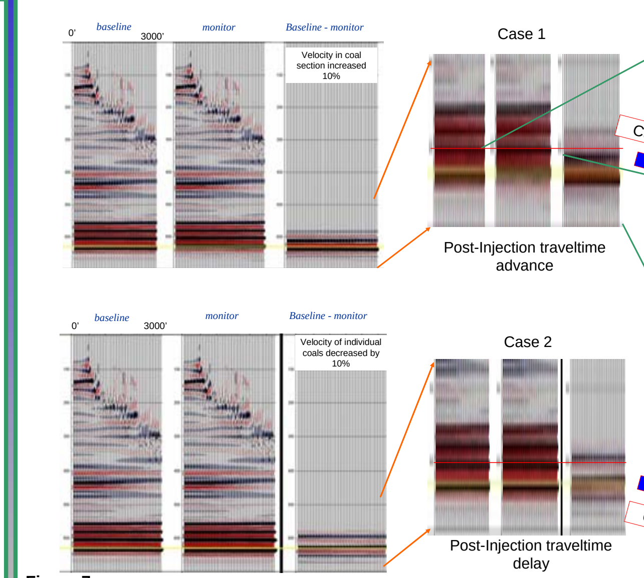
Figure 5

Time lapse comparison of monitor and baseline surveys

CMP differences (Run 2- Run 1 or monitor – baseline) are shown for offset VSPs B, C and D (Figure 5A). These represent output from the initial stage of processing. Significant amplitude response is observed throughout the differenced records. The differences are more noticeable for Offset D, particularly for the Fruitland and deeper events. The synthetic response (Figure 6C, below) indicates arrival times of approximately 0.55 seconds for the upper Fruitland.

Additional processing incorporated migration and conversion to depth along with crossequalization and non-rigid matching (Figure 5B). Crossequalization is defined by Ross et al. (1996) as a combination of matched filtering, amplitude scaling and static correction that produces a match between the baseline and monitor responses. The process is usually designed on data above the zone of interest in portions of the data unlikely to have been affected by production or injection. When applied in this fashion, the process eliminates significant difference in areas above the reservoir. Differences remaining within the reservoir and below can then be interpreted to result from possible changes of acoustic properties within the reservoir and bounding intervals. Non-rigid matching (Nickel and Sonneland, 1999) is another time-lapse process used with similar objective. This process is also generally designed on data above the reservoir. It assumes that samples (voxels) in the monitor survey are displaced versions of those in the initial survey. Samples in the monitor data set are relocated to improve the match and the relocated data form a reference survey that is subtracted from the baseline survey to provide a time-lapse view in which differences may be restricted to reservoir effects.

Results presented for crossequalization and non-rigid matching (Figure 5B) were designed on the entire data set. This represents a global design approach. Global design, in this case, effectively removed indications of change attributable to differences of acoustic properties in the reservoir and deeper intervals for offsets B and D. Differences observed in Offset C are difficult to interpret. A band of relatively high amplitude differences is observed around depths of 2700 feet (approximately 250 feet above the upper Fruitland Coal) and in depths beneath the reservoir (>3200 feet). The differences show no clear relationship to changes of acoustic properties within the reservoir.



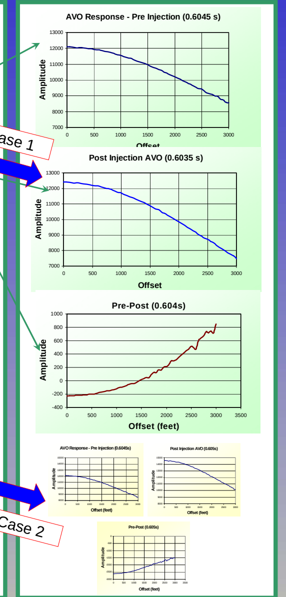


Figure 7

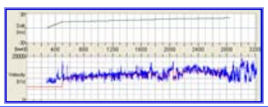
What could we expect to see in the time-lapse VSP response?

Some published studies suggest that acoustic impedance of coal will be increased by CO_2 injection due to preferential adsorption of CO_2 molecules and coal swelling. Xue and Ohsumi (2005), for example, make detailed measurements of swelling strain and waveform traveltime changes for the Kushiro Coal in Hokkaido, Japan. They note a 10% increase in P-wave velocity at 2.5 MPa (~362psi) and perhaps up to 12.7% at 12 MPa (supercritical). Nishimoto et al. (2008) report only 2.2% increase in V_p at 12MPa under supercritical conditions.

McCrank (2009) notes that CO_2 injection into the Ardley Coal, Alberta, produces a 10% reduction in velocity attributed to increased coal plasticity after a 9 month CO_2 soak.

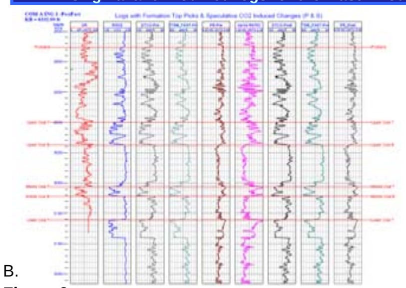
In the following section (see Figures 6 and 7) we calculate AVO variations in CMP gathers using full solutions of the Zoeppritz equations. CMP gathers in this case are used as a proxy for the VSP response. In the gathers, short to long offsets correspond roughly to upper to lower borehole sensor locations (incidence angle increases with offset and depth). Two possible scenarios are modeled: 1) CO_2 injection reduces coal velocity and 2) CO_2 injection increases coal velocity. The results suggest that in both cases significant time lapse response occurs due to relative delay or advance in the pre-to-post-injection traveltimes. The accompanying model studies evaluate potential AVO and time lapse response to CO_2 injection; present simulations for alternative cases in which CO_2 increases and decreases coal zone velocity; and, determine the potential for time lapse AVO observations in CMP and VSP records.

A.



Zero offset VSP first arrival times provided aTD curve to adjust two-way of sonic and density curves used to generate AVO synthetics.

Original and modified logs for the "fast" model. Synthetic AVO response computed for the fast case.



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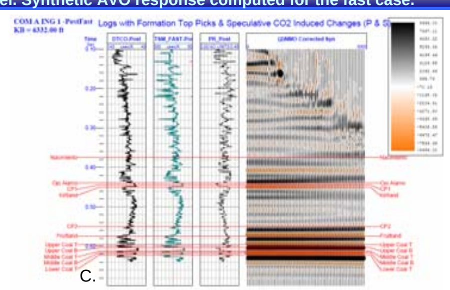

C.

Figure 6

Comparisons of synthetic baseline and monitor CMP gathers (Figure 7) showing time lapse responses for two cases: 1) increased velocity in the coal section and 2) decreased velocity within individual seams. Close-up views of the Fruitland coal section highlight differences observed for each case. AVO plots are presented for both cases. The CMP gathers are used as a proxy for the VSP response: the response at longer CMP offsets corresponds to deeper phones in the borehole VSP. For either case the time lapse response results primarily from relative traveltime delay or advance.

Conclusions

At present, results of time-lapse processing suggest that differences between the monitor and baseline surveys are minimal and do not reveal any significant change in the acoustic properties of the reservoir during the 1.3 year interval between the two surveys.

Although injection proceeded for 1 year with total injection volume of 319MMCF, the injection well was allowed to pressure down for one month preceding the VSP monitor survey. The volume of CO_2 released during the pressure down period may have significantly reduced the impact of residual CO_2 on the acoustic properties of the reservoir. The reasonable expectation in this case may be that significant differences in the acoustic properties of the reservoir should be minimal and perhaps unobservable.

However, as noted earlier, the crossequalization and non-rigid matching processes presented here incorporated a global design approach which tends to eliminate all differences between the baseline and monitor data sets. At present, we await results in which the crossequalization and non-rigid matching operations are designed on data from above the reservoir. There are inherent errors in either the global or local design approach. The potential for success using local design in the window of data above the reservoir is limited due to a lack of good signal-to-noise ratio and a lack of coherent reflection events in the window overlying the Fruitland. The results of reprocessing may continue to suggest that CO_2 induced change is not observable. This outcome would most likely be due to extensive pressure draw-down following injection.

In this study, we also modeled differences we might expect to see from CO_2 injection. Time lapse differences in two CMP attributes were evaluated: 1) AVO, and 2) traveltime delay or advance. traveltime delay or advance is a discriminating attribute whereas the difference in AVO is not. Processing and simulations suggest that differentiation between increased or decreased velocity cases may be detectable in CMP gathers or VSP surveys through crossequalization of the seismic response above the injection zone followed by careful analysis of traveltime differences between events in the baseline and monitor surveys arising from within and beneath the injection zone.

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